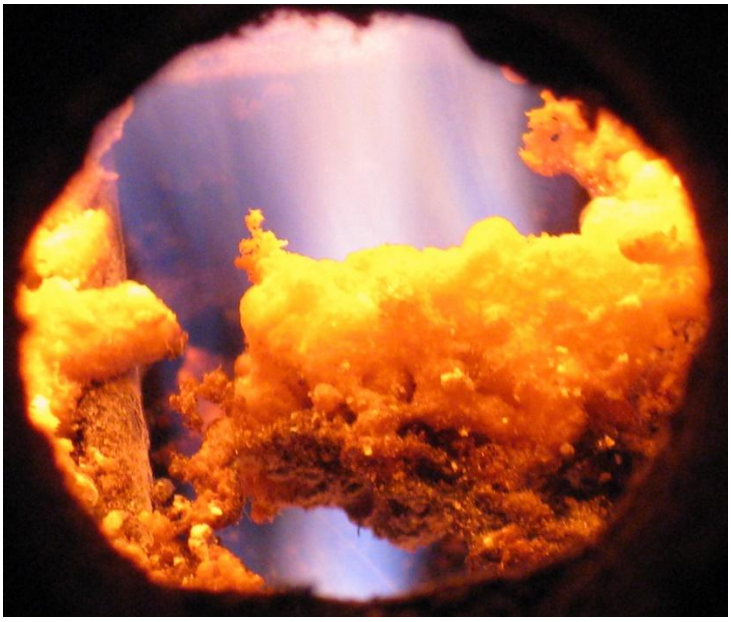
IEA Bioenergy
Technology Collaboration Programme

Residential Biomass Boiler Systems

State-of-the-art and recent Innovations

IEA Bioenergy Task 32 Biomass Combustion

November 2025



Residential Biomass Boiler Systems

State-of-the-art and recent Innovations

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Executive summary

Innovation in small-scale residential biomass combustion technologies is revolutionizing the way we think about energy production and sustainable living. As the world grapples with the challenges of climate change and the need to reduce greenhouse gas emissions, finding alternative sources of energy has become paramount. Biomass, derived from organic matter such as wood pellets or wood chips, offers a promising solution for decentralized energy production in residential settings. The development of innovative technologies in this field is enabling homeowners to harness the power of biomass and contribute to a cleaner, greener future.

Small-scale residential biomass combustion technologies have undergone significant advancements in recent years, driven by the increasing demand for renewable energy options and the need to reduce reliance on fossil fuels. These technologies encompass a range of systems and devices designed to convert biomass into heat or electricity for residential use. From pellet stoves and boilers to micro combined heat and power (CHP) units, these innovations are making biomass a viable and accessible energy source for homeowners.

One key area of innovation in small-scale biomass combustion technologies is efficiency improvement. Traditional wood-burning stoves and open fires have long been associated with low efficiency and high emissions. However, modern biomass combustion devices incorporate advanced combustion technologies, using certain gasification and/or pyrolysis steps, to achieve higher efficiency and cleaner combustion.

Moreover, innovations in emission control systems have played a vital role in improving the environmental performance of small-scale residential biomass combustion technologies. Advanced technologies, such as catalytic converters and particulate filters, help capture and minimize harmful pollutants released during the combustion process. This not only reduces air pollution but also enhances indoor air quality, making biomass combustion a healthier option for residential heating.

Another area of innovation lies in the integration of biomass combustion systems with smart and renewable energy technologies. Home automation systems and advanced control algorithms enable homeowners to optimize energy usage, monitor fuel consumption, and adjust heating settings remotely. Furthermore, coupling biomass combustion systems with solar panels or wind turbines allows for hybrid energy solutions, maximizing renewable energy utilization and reducing reliance on the grid.

In conclusion, innovation in small-scale residential biomass combustion technologies is paving the way for a sustainable and decentralized energy future. By improving efficiency, reducing emissions, integrating with smart and renewable energy systems, and enhancing fuel supply chains, these innovations are transforming biomass into a reliable, clean, and accessible energy source for homeowners. As the world seeks to transition to a low-carbon economy, these technologies offer an effective solution for reducing greenhouse gas emissions, mitigating climate change, and promoting energy independence at the residential level.

State-of-the-art technologies

Biomass combustion for residential scale has been through a long technological evolution process, which can be seen in the development of the particulate matter emission from type testing results, as well as the energy efficiency in Figure 1. Key driver for this evolution was continuously stricter emission limits due air quality issues and energy efficiency debate.

Figure 1: top: Particulate matter emission, bottom: energy efficiency of biomass boiler systems (logwood, wood chips and pellets) during full load type testing

Source: Type testing data of FJ BLT Wieselburg

The technological milestones and development roadmap of this evolution might be summarized to the following:

- **Primary and secondary air distribution** – this allowed to distinguish two distinct purposes of air in the combustion of a solid biofuel. Primary air is dedicated to complete conversion of the solid fuel to ash and a combustible gas. In a second and spatially separated step, this combustible gas is converted by secondary air addition to a complete gas burnout and minimized organic and carbonaceous emissions. Besides this, the air distribution has also an effect on the temperature of the solid phase combustion, which affects additionally the release of inorganic vapours and fine particulate matter in the flue.

- **Combustion control** – controls the fuel to air ratio during operation, which is implemented either by controlling an oxygen excess in the flue gas or by a certain combustion chamber temperature set point. These values give feedback on how much fuel has been converted or energy has been released in relation to the input air volume and is translated as the air excess ratio. Every technology has a distinct optimum in air excess ratio concerning emission release – too high air input actively cools down and dilutes the flue gas, hindering the kinetic reaction rate – too low air input decreases the availability of oxygen and the turbulence for optimal reaction, as can be seen in Figure 2.

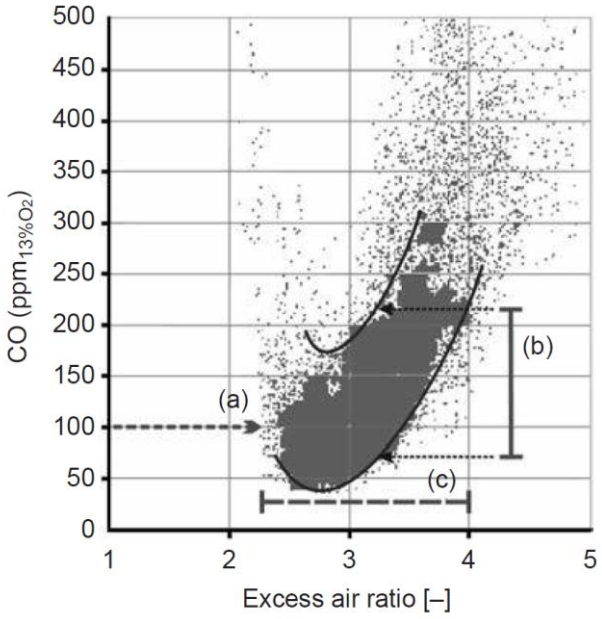

Figure 2: Correlation of air excess ratio and emission of carbon monoxide (Schwabl, et al., 2013)
(a) Minimum air excess ratio, (b) CO emission variance, (c) Air excess range

- **Load control** – allows adaption of the energy output of the boiler according to the energy demand side, thus it regulates and modulated the heat output from full to part load. The load control is intertwined with the combustion control. Depending on a setpoint of return flow temperature, the load control adopts either the fan speed of the flue gas conveying system, or the fuel feed. The combustion control needs to follow vice-versa with adoption of the other side of the fuel-air-relationship. Together they are responsible for optimal energy efficiency and lowest energy efficiency.

- **Condensing heat-exchanger** – another game changer in energy efficiency is the technology to valorise latent heat in the condensation of gaseous water vapour in the flue. This water of course originates on the one hand from water content in the fuel. However, especially at low water content, most of the water in the flue is originating from combustion of the hydrogen content in the fuel. As the reference energy value for energy efficiency calculation in the fuel is based on the lower heating value, which does not consider condensing heat, the energy efficiency increases 5 – 10% and condensing heat-exchanger technologies may even exceed 100% (see also Figure 3). However, proper materials and condensate handling are essential due to the acidic nature of the condensate.

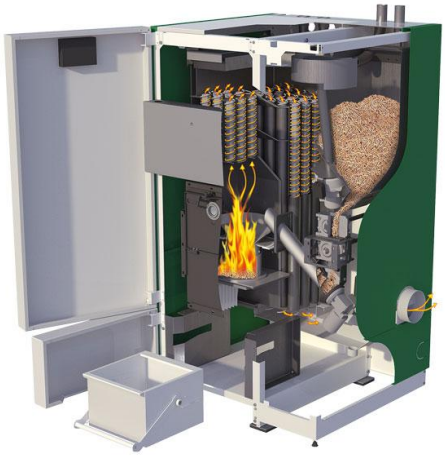

Figure 3: Pelletstar CONDENSATION by HERZ, Available for 10-100kW heat, 106% energy efficiency, for low and high-temperature radiator systems

Source: https://www.herz-energie.at/produkte/pelletkessel/pelletstar-cond/

Feldmaier et al. (Feldmaier, Schwarz, Wopienka, & Pfeifer, 2021) investigated 76 commercially available biomass combustion technologies in a nominal heat load range from 6-80 kW thermal, which were presented at the permanent exhibition at TFZ Straubing in Germany and various trade fairs in Austria and Germany in 2020. Besides categorising the technologies in terms of fuel and feeding system, they gauged the investigated technologies on certain design parameters and dimensioning of technology components.

Figure 4 gives an overview on fuel of the investigated boiler technologies. Most of them are approved for wood pellets of highest grade (A1) according to (ISO 17225-2:, 2021). But also 38% of the boilers run on wood chips according to (usually class B1) (ISO 17225-4:, 2021) or agrofuels according to (ISO 17225-6:, 2021) like miscanthus or straw.

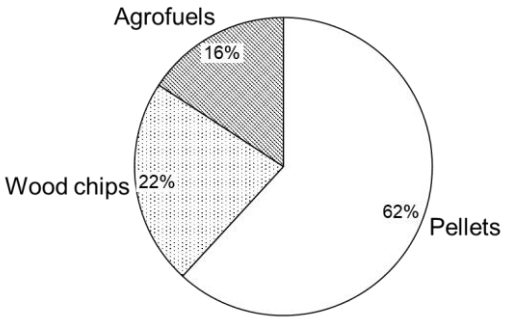

Figure 4: Fuels utilized in biomass combustion technologies

With different fuels, also different combustion technologies are addressed, as depicted in Figure 5 and Figure 6. Low ash containing and easy flowing wood pellets are combusted in a broad range of combustion technologies. The majority in small-scale combustion, however, follow a rather simple pot burner system, which is fed from the top. Most wood chips combustion feed the fuel from the side.

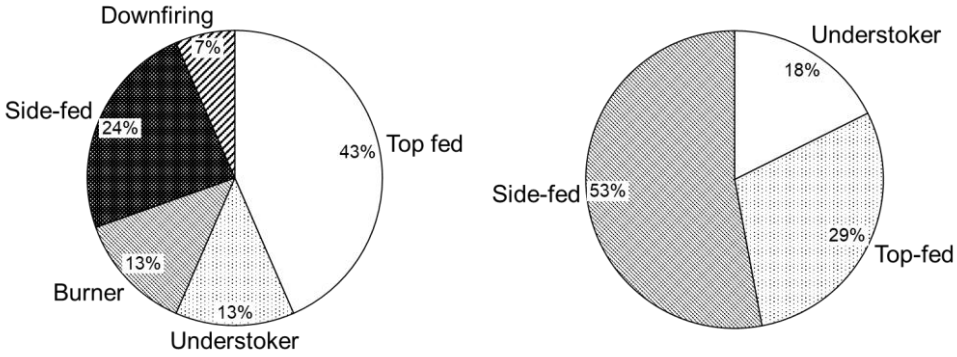

Figure 5: Feeding technologies for pellet combustion (left) and wood chips combustion (right) technologies

All pellet combustion technologies consist of a fixed grate system, whereas wood chips and agrofuel combustion increasingly utilize moving grate systems dealing with increased ash content as well as ash sintering and slag formation. This fact is also reflected in the thermic grate load of the combustion technologies, which relates the energy input flow to the surface area of the grate (see Figure 7). Low thermic grate load allows the grate to handle high ash and slag formation, while combusting agrofuels in small-scale technologies. Wood pellets on the other hand, show significantly higher thermic grate load – while also comprise a broader range due to the diversity in feeding and grate technologies for this fuel.

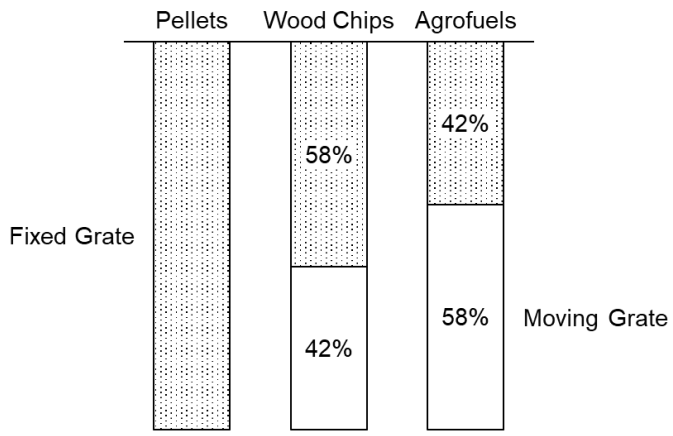

Figure 6: Grate types for different fuel combustion technologies

Figure 7: Thermic grate load of small-scale combustion technologies (Feldmaier, Schwarz, Wopienka, & Pfeifer, 2021)

In terms of emission, gas phase combustion plays a major role. Gas phase combustion is reflected in two dedicated characteristic numbers: A) Thermic volume load and B) Thermic sectional load.

- The thermic volume load relates the fuel energy input to the spatial dimensions of the so-called secondary combustion chamber, which denotes the freeboard after the secondary air supply until the heat exchanger. This characteristic number is connoted to the residence time of flue gas in the gas phase combustion zone. Thus, low thermic volume load means high residence time of gases and consequently higher potential to reduce emissions and incomplete combustion.

- The thermic sectional load relates the fuel energy input to the cross-sectional area in the secondary combustion chamber. Thus, the thermic sectional load reflects the local velocity scheme of the flue gases, meaning also the turbulence scheme. Low sectional load denotes a lower flow regime and allows formation of streaks in a low turbidity scheme. Whereas high thermic sectional load means a high turbulence and mixing of secondary air with flue gases allowing for optimal gas phase combustion conditions.

Figure 8 displays representative thermic volume load and thermic sectional load for agrofuel, woodchips and wood pellets combustion. Concerning thermic volume load, lowest values are

reached for agrofuel and wood chips combustion. This counteracts more challenging fuels in combustion. Wood pellet combustion again shows a significantly higher variance in this characteristic value, which is once again reasoned in the diversity of combustion and grate technologies. Thermic sectional load shows only very low differences between the different fuel technologies. Wood pellet combustion obviously might apply slightly lower thermic sectional load in comparison to agrofuels and wood chips – the difference, however, is not very significant.

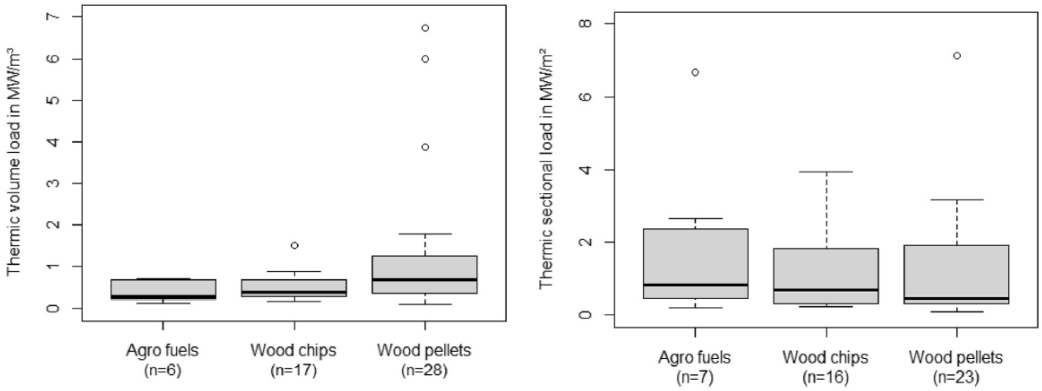

Figure 8: Dimensioning of combustion technologies based on characteristic numbers (thermic grate load, thermic volume load and thermic sectional load) (Feldmaier, Schwarz, Wopienka, & Pfeifer, 2021)

Innovative Technologies

New technologies for biomass combustion were developed during recent years to increase boiler efficiency and to reduce emissions of particulate matter, unburned gaseous organic compounds and nitrogen oxides.

BOILER TECHNOLOGY

Although the high development level of biomass combustion there are still new technological developments.

Combustion technology

Several new advanced combustion technologies were presented from biomass boiler manufacturer during the last years. Advanced combustion techniques should reduce the emissions of biomass furnaces to a level close to zero without secondary abatement technologies.

Updraft Gasification

Biomass combustion by gasification is a feasible method to reduce particulate matter emission by primary measures. Gasification is a process that converts biomass based carbonaceous materials into burnable gases. There are two main types of biomass gasification systems—updraft and downdraft.

Updraft gasification combines two known measures of emission reduction, extreme air staging and low dust combustion. The system consists of a gasifier and a gas combustion unit which is installed directly above. An updraft gasifier is a counter current flow reactor were this kind of

incomplete combustion takes place. Biomass is feed at the top of the gasifier and ash is removed through the grate at the bottom. In contrast, primary air enters the system near the bottom and combustible gases exit on top. The gasification operates with a well-defined air stream at a very low excess air ration inside the combustion zone, so the system must be very tight. Therefore, the gasification process works at lower temperatures as combustion and evaporation of salts in the ember layer is reduced. During the flow of the combustible gases through pyrolysis and drying zone inorganic aerosols precipitate the feed stock. The product gasification gas of is low in particulate matter but high on tar, but combustion is easier because of its state.

Austrian company Windhager Zentralheizung GmbH produces boiler for chip wood and pellets based on this combustion principle having nominal power in the range of 24 to 103 kW. Despite the voluminous gasifier unit, these boilers remain similar in size to traditional ones. Without any further dust reduction measures the particulate matter emissions of this kind of boiler are down to 1-2 mg/m^3_{stp} $10\%O_2$.

Figure 9: PuroWIN by company Windhager, updraft gasifier with direct combustion
Source: https://www.windhager.com/de-at/produkte/hackschnitzelheizung/purowin/

Factbox PuroWIN Windhager

Updraft gasifier for wood chips and pellets
7-103 kW heat output
93-94% energy efficiency
Ultra low emission
Dust: 1-2 $mg/m^3_{stp,10\%O2}$

Downdraft gasification

In downdraft gasifiers, fuel and burnable gases both flow in the same direction, these are concurrent flow reactors. Different to updraft gasifiers, gases which are produced inside the pyrolysis zone pass the high temperature region (combustion and reduction zone), where tars and hydrocarbons are cracked. So, product gas has a higher amount on hydrogen and a lower tar concentration. Because fuel is not preheated by gases, thermal integration of down draft gasifier is weaker compared to updraft, so requirements on feed stock are higher. The maximum moisture content should be below 10 – 15%, and the amount of fine particle should be low to have a constant pressure drop over the fuel bed.

Most of the feedstock's energy is chemically stored in the gasification gas; therefore, the direct heat output is low. Downdraft gasifiers usually include a gas cleaning unit, like a particulate filter to reach gas quality which is necessary for gas-engines. Fixed bed gasifiers are well suited for small-scale CHP applications which are available e.g. from Hargassner GesmbH or Fröling Heizkessel- und Behälterbau GesmbH, who produces a gasifier for pellets too. For more details see chapter Combined Heat and Power (CHP) at page 20. But they can also to be used to produce fuel gas for burner in industry.

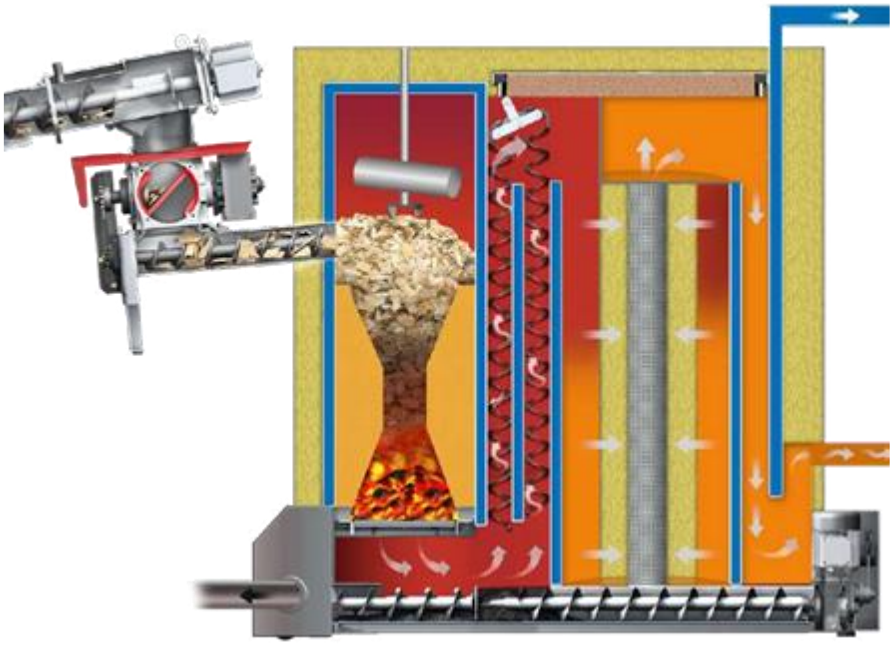

Figure 10: Hargassner CHP-gasifier unit

Source: https://www.hargassner.com/wp-content/uploads/2022/08/kwk-prospekt-de.pdf

Factbox Hargassner KWK gasifier unit

Downdraft gasifier for Wood chips
direct heat output 16kW
95% energy efficiency

Flameless combustion

Zero Flame Combustion was invented by ÖkoFEN Forschungs- und Entwicklungs GesmbH. in 2020 and the company is now implementing this technology into their product range on pellet boilers.

Based on their pellet combustion system using a multisegmented firing plate they use a special combustion chamber design and a guided airflow combined with a flue gas recirculation system to reduce the oxygen amount of primary and secondary air. By these measures the temperature of the ember layer on the grate is reduced which lowers evaporation of inorganic substances from the fuel bed and reduces particulate matter to a minimum. Additionally, the secondary air is preheated inside the injection lance before it enters the combustion zone to speed up combustion reactions of the gases, so as special effect the flame disappears almost completely.

This technology is still in development, currently it is only available for Ökofen's pellet boiler up to 18kW nominal capacity.

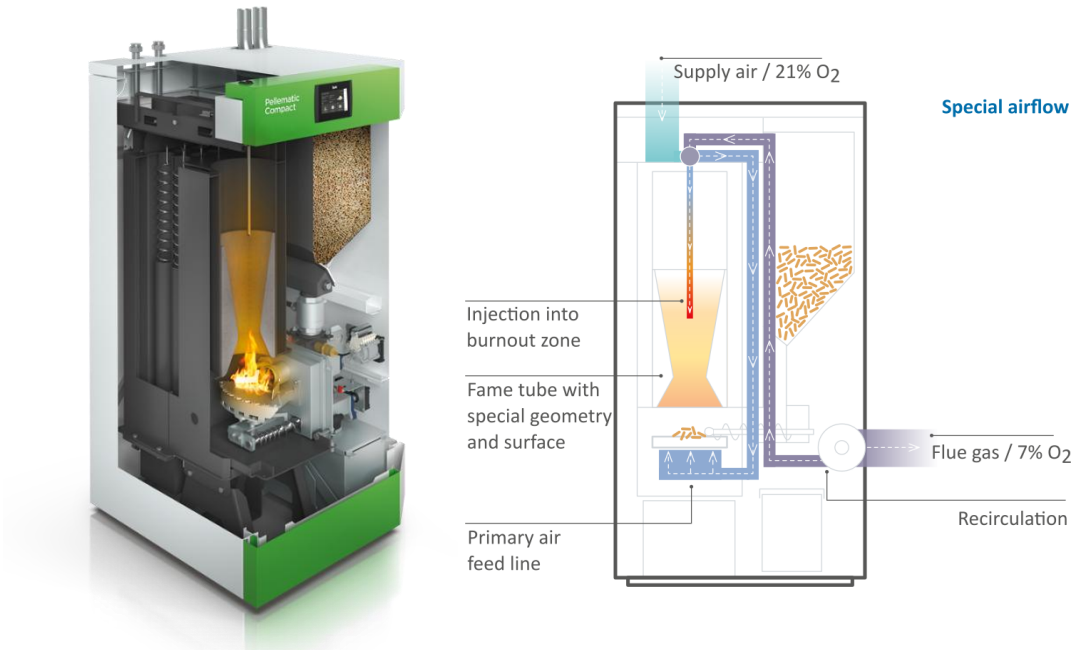

Figure 11: Pellematic Compact by Ökofen, zero flame technology

Source: https://www.oekofen.com/de-at/pellematic-compact/

Factbox Ökofen Pelletmatic Compact with Zeroflame-Technology

Available for 3-18kW heat
97,5% energy efficiency
< 1 mg/m3stp,10%O2 particulate matter emission at continuous operation

Control strategies

Several companies developed advanced control strategies and use additional sensors to minimize emissions and to optimize economical operation of municipal heating plants.

Fuel

E.g. revolution adaptive control from Schmid AG energy solutions is a control strategy for boiler which are operated with often changing fuel or variable fuel quality. Humidity of biomass feedstock is an important parameter which influence not only heating value of fuel, it has a huge effect on some other combustion parameters like grate temperature too. To achieve a stable boiler operation predictive control strategy is preferable, because huge boilers have a long delay if response-based controller is used and therefore they only slowly react on changes. Using sensors for humidity of fuel, combustion chamber temperature and size and height of ember layer on grate, Schmid's revolution adaptive control continuously determines fuel quality and reacts fast on fuel changes which results in stable combustion and heat output.

Factbox Schmid Revolution Adaptive Control

Available from 700kW heat output
2,5% higher energy efficiency

Cycle Test Method

The Load Cycle Test Method is a practical test for assessing the efficiency (degree of utilization) and the emission behaviour of domestic wood central heating systems in real operation. The method is suitable for automatically fed pellet and chip boilers.

The methodology of the Load Cycle Test should enable manufacturers of high-quality wood-fired boilers to demonstrate the high efficiency and emission behaviour of their products in everyday use, to identify and highlight particularly advanced technologies. The Load Cycle Test simulates the real-life operation of a boiler which is either directly connected to a building's heating circuit or connected via an accumulator storage tank. Therefore, the heat output of the boiler shall vary according to a standard load pattern.

The entire test cycle includes all the phases of boiler operation (cold start, warm start, varying heat demand, steady-state operation at different loads, shutdown, and standstill) and allows the measurement of the annual standard efficiency and the annual standard emission factors in a short period of time. Due to dynamic measurements, the test stand setup is an enhanced version of the setup necessary for type test method according to (EN 303-5:, 2023). It requires additional measurement infrastructure, particularly in terms of determination of flue gas velocity, a transient way of particulate matter (PM) sampling, and a heat transfer system which controls a defined and variable heat demand (i. e. capable of water flow rate variation).

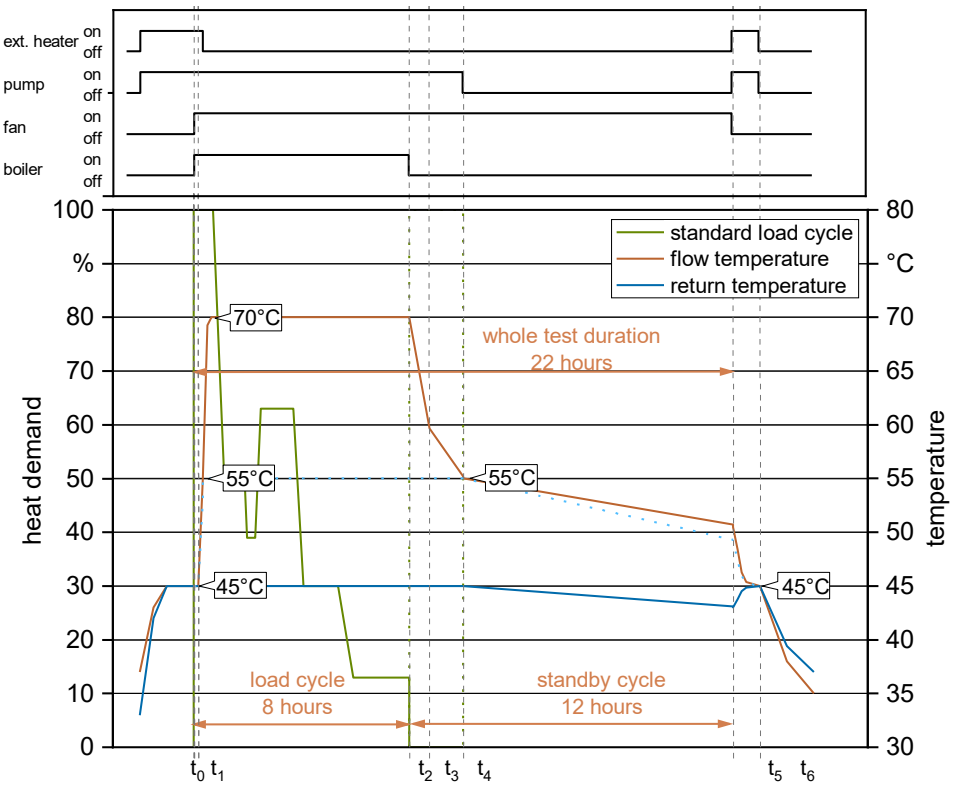

Figure 12: Flowchart of test sequences during a Standard Load Cycle Test for a conventional boiler.
Source: https://www.tfz.bayern.de/publikationen/berichte/339753/index.php

The method was tested in a round robin test, and in a serial study of a total of 11 central heating systems (8 × pellets, 2 × wood chips, 1 × heating oil) as data basis for the assessment of the real emissions and efficiency of automatically fed domestic wood heating systems. A detailed test bench manual for the method is freely available, to provide boiler manufacturer the possibility to rate their products (Feldmeier, Schön, Hartmann, Schwarz, & Roßmann, 2023).

Emission abatement

As secondary measures for reduction of particulate matter emissions electro filters are widely used in biomass furnaces.

An electrostatic precipitator (ESP) transfers electric charges on particles and separates them by applying an electric field towards a deposition anode. For this reason, separation efficiency also for submicron particles may still exceed 90%. Different to other dust collectors an ESP applies energy only to the particulate matter being collected and therefore is very efficient in its consumption of energy, and easy in maintenance as there are no direct moving parts. Major development issues now address re-entrainment of already separated particulates and application in high temperature environment.

Different kinds of electro filters are on marked available. In Figure 13 an accessory filter device is shown, which is directly mounted in the chimney and works independent from the boiler. Over the last years boiler manufacturer started first to sell attachable filter, which are mounted directly on the boiler and now there are a lot of boiler from different manufacturers on marked which have integrated the ESP in the boilers heat exchanger, as can be seen in Figure 14.

Figure 13: Particle separator by Atmos

Source: https://atmos-zentrallager.de/zubehoer/partikelabscheider

Factbox particle separator by Atmos

Available for combustion systems with nominal power of 25-50kW

Advantage of direct connection from the ESP to the boiler and its controller is that the boiler gets feedback if primary dust emissions are too high and can vary its operating conditions to ensure minimum dust emissions. During boiler standby phases it can also switch the ESP on and off to reduce its overall energy consumption. Direct implementation of the ESP into the boiler has for consumer additional advantages like they do not have to clean it, this is done by heat exchanger cleaning and ash handling. A major issue though is that ESPs are neither applicable at the entrance of a heat exchanger, due to high temperatures, nor at the exit of condensing heat exchangers, due to condensing conditions. This means, that the ESPs need to be integrated directly in the heat exchanger. This allows the utilisation of heat exchanger as a deposition anode. The increase in deposition rate on the heat exchanger, however, need increased cleaning intervals on the heat exchanger to maintain high energy efficiency.

Figure 14: PE1c Pellet by Fröling with integrated electrostatic precipitator

Source: https://www.froeling.com/de-de/produkte/pellets/neu-pe1c-pellet/

Factbox Fröling PE1c Pellet

Available for 15-20kW heat
106% energy efficiency
Combination of condensing heat exchanger and electrostatic precipitator

SYSTEM INTEGRATION

Home automation

Today most boiler or boiler controller producers provide visualisation apps for monitoring and remote control of their heating system. They can check the status of the system, adjust temperature settings, and even troubleshoot issues from their smartphones or computers.

Usually there are two different kinds of apps for remote supervision used, either a virtual network connection to the boiler's user interface or web-based mobile app connected to a server mostly owned by the boiler manufacturer.

In case of web-based apps for supervision, the boiler sends periodically it's data to this server and checks for any new operation requests. Therefore, the boiler manufacturer must provide server storage and computational time to each costumer, but he gets the operational data

from each heating installation which provides him the opportunity to use the data to optimize his products or for training of a machine learning based AI systems. In this case, costumer can automate tasks, using services like IFTTT or Microsoft Power Platform for web-based applications, they can connect their boiler to other devices, which allows to set up a simple home automation system without any local server or hub.

Figure 15: KWB Comfort Online Control

Source: https://www.kwb.net/de-at/produkte/regelung-und-bedienung/kwb-comfort-online/

Common home automation systems usually use a local smart home hub to connect all devices independent from the WAN. They monitor and/or control home attributes such as lighting, heating, ventilation and may also include home security such as access control and alarm systems. So, the hub is connected by cable or via wireless radio signals to smart home ready devices like room thermostats, boiler, electric plugs, lamps and to voice controlled devices like Orinoco Alexa or Poodle Nest which could be used to control home appliances or systems.

In 2024 14.2% of all Europeans used internet connected solutions for energy management for their home, it is a strong growing market (Eurostat, 2024)

Integration of biomass boiler into Smart Home Hub Ecosystem should optimize the energy demand of buildings to reduce energy costs and carbon dioxide emissions. Therefore, Smart hubs use data from a broad range of sensors including occupancy sensors, so the building is only heated if residents are present. They could also use more complex energy management algorithm and consider forecast data too.

Biomass boiler typically uses buses like KNX, LON or ModBus via RS-485 or LAN for communication with the smart home hub. Some smart hub manufacturers like LOXONE Electronics GmbH. provide special hardware modules for boiler communication. In the moment, no boilers are certified for the new smart home communication standard matter® from Connectivity Standards Alliance.

The amount on data accessible and available control options depends strongly on the boiler manufacturer. In the simplest case, home automation system can only switch the boiler or the heat distribution system on or off, in some cases it is possible to modify boiler or flow set temperature. But control abilities on boiler are always limited, Smart home systems should not modify combustion conditions.

Figure 16: ETA connection to LOXONE interface

Source:https://www.eta.co.at/index.php?id=151&download=7ab70b6fe14423b290d63a975c97d7a0

Forecasting / AI utilisation

By introduction of boiler with colourful touch user interfaces (human machine interface HMI) on the marked boiler got not only additional connection possibilities, which are used by IoT and for home automation, they also got an additional powerful microprocessor, so the boiler has new possibilities for advanced controller algorithm for heating system or improved combustion control or boiler surveillance.

Over the network connection the boiler controller from e.g. SOLARFOCUS GmbH receive weather forecast data. This allows a more precise evaluation of the buildings heat demand. Especially if an additional solar thermal collector is installed, see also Hybrid systems on page 18.

Increasing computing power enables the ability to use self-adapting control algorithm, neuronal networks and Artificial intelligence. AI plays an increasingly important role in control systems in various fields. By using machine learning algorithms, AI can develop complex control systems that can adapt to changing conditions. This enables more precise and efficient control of processes and systems. Additionally, AI can help solve control problems that are too complex for traditional control methods. Overall, AI offers many advantages in control systems, but a lot of training data is required to learn the AI. Currently, only the boiler from Sommerauer SL Technik GmbH uses AI. It is an add-on to its basic controller; it improves boiler settings based on operational data.

Figure 17: Sommerauer LOOP+ AI for ECOS

Source: https://sommerauer-energie.com/wp-content/uploads/2022/01/Kuenstliche-Intelligenz-LOOP.pdf

Hybrid systems

A hybrid system is a biomass boiler combined with another energy source like thermo-solar panel, solar panel or a heat pump and sometimes also energy storages. The fundamental issue is that they are not independent devices, all energy sources are managed by one controller which optimizes the energy efficiency of the whole system. So, hybrid systems always use the most efficient device for heat generation and should also take care which energy sources are available in next future, so weather forecast is often used by the controller.

The combination of a biomass boiler with solar thermal modules is widely used since many years, where hot tap water is produced during summertime by solar power and only in winter from the biomass boiler. During last years, combinations of biomass boiler and heat pump were more often seen on market, because boiler have a better efficiency on cold days and heat pump performs best at intermediate temperatures. Biomass boilers can also provide the base load heating demand, reducing the cycling frequency that often leads to higher emissions and lower efficiency, while heat pumps serve as auxiliary systems to handle variable or peak loads. It is also possible to include photovoltaic panels into the system, they provide electricity for operation of the heat pump during transitional period, excess electricity could be either sold or used to heat water in a storage tank.

Figure 18: Solarfocus ecotop^{zero} with CPC - solar collector

Source: https://www.solarfocus.com/en/products/solar-system/cpc-panels?_ptp=12

Factbox Solarfocus ecotop^{zero} with CPC

15-24 kW nominal load available
8-10 m² solar thermal collectors allow 20-30% reduction of fuel
weather forecast for load management

The combination of different technologies and energy sources allows to manage energy flow intelligently and optimizes the use of resources based on demand and availability. This flexibility leads to improved energy efficiency. Overall, hybrid energy systems in residential buildings enable homeowners to reduce their primary energy consumption and to achieve greater energy independence. Hybrid systems have still higher investment costs, compared to single heating systems, but their economy over life is better. Particularly in times of high energy prices the public interest in such systems is high.

Figure 19: Windhager BioWin2 or LogWIN with AeroWin heat pump

Source: https://www.windhager.com/de-at/produkte/hybridheizung/biowin2-hybrid/

Factbox Windhager BioWin2 Hybrid with AeroWin heat pump

Pellet boiler 10-26kW nominal load (93,8-94,8% energy efficiency)
Heat pump: 3- 6kW nominal load (COP 2,8-3,5)
2 functions: cost optimized (costs for electricity and pellets) or comfort optimized (depending on external temperature)

CO-PRODUCTION

Generally, co-production means there is an additional product to heat during combustion. In case of biomass combustion typical coupled products are electrical power and biochar. It allows a better utilization of biomass fuel and makes small-scale biomass combustion more diverse.

Combined Heat and Power (CHP)

CHP systems simultaneously produce heat and electric energy. In times of high electricity costs, they get more interest on market.

Micro combined heat and power (µCHP) technologies for residential homes have been developed but only few of them are still available on the market. Because of the high investment costs, low electricity costs over a long time and weak electrical output ratio the market response was low. One example for this kind of devices is the Stirling engine from ÖkoFEN Forschungs- und Entwicklungs GesmbH. It can be installed in their boiler of the Pellematic series and produces in addition to 10-16kW of heat also 600W of electrical power.

In contrast the marked for medium CHP technologies is growing because of the shift away from fossil fuels. These most common system in this market are biomass gasifier combined with gas-engines for direct utilisation of the gasifier gases. Such devices are built from a couple of manufacturers, also from some traditional boiler producer like Hargassner GesmbH or Fröling Heizkessel- und Behälterbau GesmbH. Compared to µCHP these systems have a better electricity output rate in the range of 25 to 35%, so they can provide electricity for up to 5 times more homes than heat. Around 75% of heat release of CHP's is from gas-engine over cooling water and flue gas heat exchanger, only 25% are produced by the gasifier. The ability of CHPs to adapt load is limited. Most time its either not possible or not recommended by manufacturer, so they are primary used to cover base load. Different to boiler, support need and service intervals of gas-engine-based CHPs are much higher, for most appliances a minor daily check is recommended. Products on market cover a power range on fuel input from 80 to more than 1500 kW.

The main market segments are district heating, small and medium industrial facilities and agricultural firms.

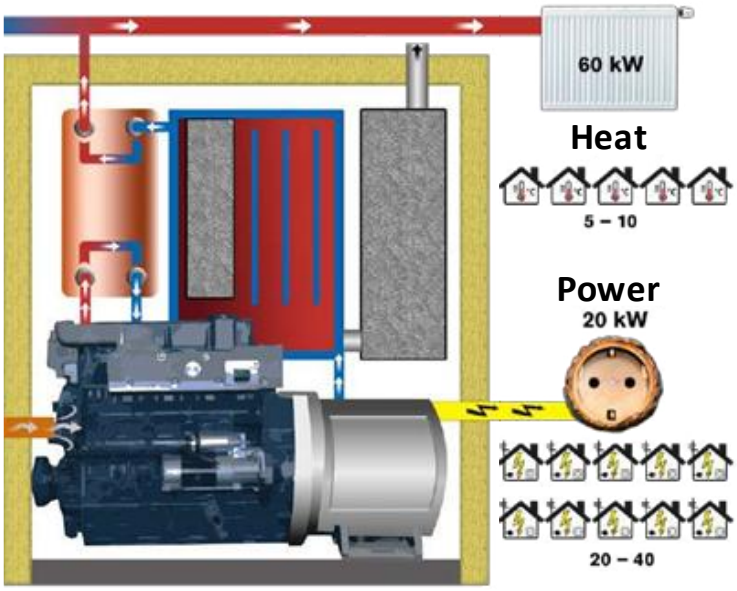

Figure 20: CHP internal combustion engine with power generator

Source: https://www.hargassner.com/wp-content/uploads/2022/08/kwk-prospekt-de.pdf

Factbox Hargassner CHP unit

20kW electricity
16 + 45kW Heat output
Water cooled engine and generator
Flue gas catalyst

Biochar Co-production

The ability to produce biochar is an additional example for co-generation for residential biomass heating systems.

Biochar has become a focal point of multidisciplinary research because of its broad application, and promising development prospects. It can contribute to a circular economy or used for long term carbon storage. Research on the application of biochar in the areas of agriculture and environment conservation has increased in the face of food security and environmental pollution. Biochar is a carbon rich residue that is produced via pyrolysis, by direct thermal decomposition of biomass in the absence of oxygen.

Powerchip Biochar from manufacturer GUNTAMATIC Heiztechnik GmbH is a chip wood boiler which can produce biochar during heating. This is achieved by incomplete combustion on grate and quenching of glowing char with water.

In contrast BIOMACON GmbH offers biochar pyrolysis plant, which also produce heat.

Both systems can adapt their load to the buildings heat demand.

Figure 21: Guntamatic POWERCHIP Biochar

Source: https://www.guntamatic.com/heizungen/pflanzenkohleheizung/

Factbox Guntamatic POWERCHIP Biochar

Up to 25% Biochar production
for wood chips G50/W40
50 to 100kW nominal load

Impact driven by innovation

	Boiler technology			System integration			Co-production	
	Combustion technology	Advanced controls	Emission abatement	Hybridsystem	Home Automation	KI / Forecasting	CHP	Biochar
energy efficieny	+	+	+	o	o	o		
emission reduction	+	+	+	+				
Cost effectiveness	o	o		+	+	+	+	+
sector coupling				+	+	+	+	+
user friendliness					+	+		
carbon sequestration								+
Circular economy								o

Table 1: Overview of impacts driven by innovation

(+ denotes direct impact of innovation, whereas o denotes an enabling technology for this impact)

ENERGY EFFICIENCY

Energy efficiency relates usable energy to the applied energy, which has been released by the fuel during combustion. The difference between usable and applied energy are energy losses, which are released by the flue in terms of sensible and latent heat, incomplete combustion and release as gaseous emission or as carbonaceous residues, radiation and/or convection to area of installation.

Condensing heat exchangers in residential combustion systems have a significant impact on energy efficiency. These innovative devices recover and utilize the latent heat contained in flue gases, which would otherwise be wasted. By cooling the flue gases below their dew point, condensing heat exchangers cause water vapor to condense, releasing a substantial amount of latent heat that is then transferred to the heating system. This efficient utilization of the latent heat greatly enhances the overall energy efficiency of residential heating, resulting in lower energy consumption, reduced fuel bills, and a decreased carbon footprint.

Another critical technology for energy efficiency is the ability of the biomass combustion to modulate the energy output. Modern combustion technologies seldomly operate under full load conditions, which is also reflected in the recently developed Cycle Test – in certain phases they are also confronted with demands of ~10% of nominal load and less. Biomass combustion systems equipped with advanced load controls can operate at variable output levels output (e.g. such as down to 10% of nominal load), responding to fluctuations in heat demand. This flexibility allows for better matching of energy supply to demand, avoiding the need to operate at full capacity during periods of low heat demand. As a result, the system operates more efficiently and consumes less fuel overall.

Hybrid energy systems in residential-scale applications have a profound impact on energy efficiency. These systems combine multiple renewable energy sources, such as solar panels, thermo-solar panels, heat pump technologies, and biomass combustion, with energy storage and smart control technologies. By integrating diverse energy sources, hybrid systems can capitalize on individual system advantages. Solar panels deliver energy at almost zero operational costs; but they depend on sun light and don’t provide energy during night. Heat pumps have high advantages at low heating demands and at outside temperatures above zero. But as soon, as temperature drops, the coefficient of performance is dropping as well. This is when biomass combustion technology can deliver time-independent and highly efficient energy. Thus, combining diverse technologies allows to intelligently manage energy flow, optimizing the use of available resources based on demand and availability. This flexibility leads to improved energy efficiency, as homeowners can harness renewable energy when it is most abundant and cost-effective. The integration of energy storage further enhances efficiency by capturing excess energy for later use. Overall, hybrid energy systems in residential settings enable homeowners to reduce their energy consumption and achieve greater energy independence.

Finally, home automation as well as utilisation of AI and forecasting technologies allow to optimize the operation residential biomass combustion technologies and maximize efficiency by optimally planning and timing of consumption and production of energy. Home automation allows for precise control over heating schedules, temperature settings, and fuel consumption. It enables homeowners to program their biomass combustion technologies to operate at optimal efficiency levels, adjusting settings based on occupancy patterns. Additionally, home automation systems can monitor and analyse energy consumption data, providing valuable insights for further energy-saving measures. This user-centric demand

forecasting can be combined with other e.g. weather forecasting, reflecting influences outside of the building envelope on the energy demand. Consequently, by leveraging home automation and forecasting systems, residents can ensure that their biomass combustion technologies are operating at peak efficiency and maximizing the use of biomass fuel resources. Ultimately, the combination of home automation and biomass combustion technologies leads to substantial energy savings and a more sustainable residential heating solution.

EMISSION REDUCTION POTENTIAL

Biomass combustion technologies emit fine particulate matter, organic gaseous compounds as well as nitric oxide emissions. All these emissions are affecting human health and air quality; thus, elimination is of high importance for biomass combustion technology as a clean and sustainable energy provision technology. This is also reflected in a consequent and consistent endeavour to develop new technologies for emission reduction.

The combined impact of advanced combustion technology, electro-filters, as well as hybridization of heating technologies, home automation, and weather forecasting have significant potential for emission reduction in residential biomass combustion. Electro-filters, also known as electrostatic precipitators, are effective in capturing fine particulate matter and reducing emissions from biomass combustion. By removing pollutants before they are released into the atmosphere, electro-filters help improve air quality and reduce the environmental impact of residential biomass combustion.

Advanced combustion technology plays a vital role in emission reduction by ensuring more efficient and cleaner combustion. Innovations such as gasification and pyrolysis enable complete and controlled combustion, minimizing the formation of harmful byproducts. Additionally, lower temperatures in the fuel bed minimize evaporation of inorganic salts and consequently reduce emission of particulate matter. In combination with advanced combustion controls, these technologies optimize the burning process, resulting in reduced emissions of carbon monoxide, and volatile organic compounds.

Big emission reduction potential is also expected by assessing small-scale biomass boilers according to their real-life operation. In Europe, small-scale biomass boilers are type tested according to standard (EN 303-5:, 2023), which investigates full and part load conditions. This testing standard is also the reference method for emission thresholds, which means that small-scale biomass boiler developments were made to reduce emissions under these conditions. In real-life, however, boilers are addressed with a broad variance of load demands, and the major question is, how does the boiler react to this demand. For this reason, the cycle test (Feldmeier, Schön, Hartmann, Schwarz, & Roßmann, 2023) has been developed, which allows to test biomass boilers close to real-life operation. Optimizing and developing combustion technology by applying this method has a huge impact on emission reduction.

Similar to effects on energy efficiency, the hybridization of heating technologies, combined with home automation and weather forecasting, further enhances emission reduction potential in residential biomass combustion. These technologies allow to optimize operation conditions of combustion technology in relation to the energy demand. Applying intelligent energy management, biomass combustion technology can be operated with priority in operation modes of lowest emission release.

In summary, the combination of electro-filters, advanced combustion technology, hybridization of heating technologies, home automation, and weather forecasting holds tremendous potential for emission reduction in residential biomass combustion. These technologies work together to capture particulate matter, optimize combustion processes, diversify energy sources, and intelligently manage energy usage based on demand and weather conditions. By implementing these measures, emissions from residential biomass combustion can be significantly reduced, leading to improved air quality, mitigated environmental impact, and a more sustainable approach to residential heating.

COST EFFECTIVENESS

Costs for energy have recently become even more pressing with respect to regional availability and dependence of fuel imports. Thus, strategies for cost effectivity have different dimensions: High energy efficiency and application of low-price fuel – diversification of energy technology to decrease the dependence – valorisation of co-products.

Advanced control systems, as well as home automation and forecasting technologies, allow operators to optimize their energy production process to achieve higher efficiency levels. By accurately forecasting energy requirements, operators can adjust their systems accordingly to avoid energy wastage and unnecessary costs. This proactive approach helps in maintaining a balance between energy supply and demand, leading to improved cost efficiency.

Integrating hybrid technologies in biomass combustion systems allows for the utilization of multiple energy sources. This flexibility enables operators to choose the most cost-effective fuel based on market prices, availability, and energy demand. By switching between different fuels or energy sources, operators can reduce costs and maximize efficiency.

CHP systems as well as biochar co-generation diversify the output of small-scale biomass combustion technologies and to generate an additional income source. Electricity is either used for own purposes and for grid independency or can be sold via smart meters to his/her energy contractor. Biochar is a valuable material that can be used for soil improvement, carbon sequestration, and other applications. Consequently, by co-generating biochar alongside energy production, operators can create additional revenue streams, reduce dependency on other energy sources and enhance the overall cost efficiency of the system.

In conclusion, the integration of advanced controls, hybrid technologies, forecasting tools, CHP systems, and biochar co-generation in small-scale biomass combustion technologies offers significant cost efficiency potentials. By optimizing the combustion process, utilizing multiple energy sources, forecasting energy demand, co-generating heat and power, and producing valuable by-products, operators can achieve higher efficiency levels, lower operating costs, and overall improved cost efficiency in their biomass combustion systems.

SECTOR COUPLING

Sector coupling is of paramount importance in achieving a sustainable and efficient energy system. It involves the integration and coordination of different sectors, such as electricity, heating, transportation, and industry, to optimize energy generation, consumption, and storage. By coupling these sectors, we can achieve higher energy efficiency, better resource utilization, and reduced environmental impact. For example, integrating renewable energy sources like solar and wind power with electric vehicle charging infrastructure enables the use of clean energy for transportation, reducing reliance on fossil fuels. Similarly, coupling heating and electricity sectors through technologies like CHP allows for simultaneous heat

and power generation. Consequently, sector coupling promotes a holistic approach to energy management, fostering a more resilient and sustainable energy system that can address the challenges of climate change, resource depletion, and energy security. It refers to the integration and coordination of different sectors, such as electricity, heating, and transportation, to enhance overall energy efficiency and sustainability. Recently, several innovations have been introduced, which will contribute to sector coupling: Hybrid residential heating technologies, combined heat and power (CHP), and biochar production have a transformative impact on sector coupling. Whereas home automation in combination with weather forecasting can be seen as enabling technologies.

Hybrid residential heating technologies, such as systems that combine biomass combustion, solar thermal, and heat pumps, enable the simultaneous utilization of multiple energy sources. In combination with home automation and forecasting systems, the choice of energy source is based on current availability of energy (e.g. wind, solar, water, …) or on other needs (e.g. level of energy storages). This coordination not only maximizes energy efficiency but also facilitates the integration of the heating sector with the broader and connected energy system.

CHP is another crucial component of sector coupling in residential heating. CHP systems simultaneously generate heat and electricity from a single fuel source. These systems can utilize biomass fuels, to produce both heat for residential heating and electricity for on-site consumption or grid export. By coupling CHP with hybrid heating technologies and home automation, the heat and electricity produced can be intelligently distributed and optimized within the residential setting, enhancing efficiency and reducing reliance on external energy sources.

Furthermore, the integration of biochar production in residential heating systems has the potential to significantly reduce carbon emissions and contribute for a circular economy (see also chapter Carbon sequestration & circular economy at page 28). This also denotes a coupling of different sectors. Coupling of energy with climate relevance is already quite advanced – technologies like CCU (carbon capture utilisation) and CCS (carbon capture storage) drive this coupling for large scale energy technologies. However, coupling with a circular economy in the field of energy production is rather new. Historically, combustion has always been the end of the cascadic utilisation. But with biochar a new valuable product is now established also in small-scale biomass combustion. This has the potential to couple even various sectors, depending on field of biochar application: agriculture as soil amendment, steel industry as bio reducer, plastic composite material, …

USER FRIENDLINESS

Home automation and forecasting technologies can significantly enhance the user-friendliness and efficiency of small-scale biomass combustion systems. These may comprise:

- **Remote Monitoring and Control**: Home automation systems allow users to monitor and control their biomass combustion systems remotely. They can check the status of the system, adjust temperature settings, and even troubleshoot issues from their smartphones or computers. This level of convenience enhances user experience and reduces the need for manual intervention.

- **Increased Comfort**: With forecasting technologies, users can set their desired temperature levels and schedules in advance. The system then adjusts the biomass combustion process

to maintain these settings, ensuring a comfortable indoor environment. Users can wake up to a warm house in the morning or return to a cozy home after a long day, without having to manually control the system.

- **Automated Maintenance Alerts**: Home automation systems can detect potential issues with the biomass combustion system and alert users in real-time. This proactive approach to maintenance helps prevent costly breakdowns and ensures the system operates smoothly. Users can schedule maintenance checks or repairs promptly, minimizing downtime and inconvenience.

- **Integration with Smart Home Ecosystems**: Biomass combustion systems can be integrated into broader smart home ecosystems, allowing seamless interaction with other devices and systems. For example, users can integrate their heating system with smart thermostats, lighting controls, and security systems for a more comprehensive home automation experience.

CARBON SEQUESTRATION & CIRCULAR ECONOMY

Circular economy and carbon dioxide removal are two important topics towards a future with bio economy and climate change mitigation. In a circular economy there are no residues, because they are completely reduced, reused and finally recycled – this applies on a global but also in particular on a regional and local level, to minimize also transportation and logistics. Active carbon dioxide removal and storage is essential to limit climate change. According to IPCC report of 2023, we have reached already a temperature increase of 1.1° - chances in meeting a 1.5° target are zero. This means it is not enough to just stop emitting carbon dioxide – it is mandatory to actively remove carbon dioxide from the atmosphere to mitigate climate effects as much as possible.

Biochar is a stable form of carbon produced from biomass through incomplete combustion. Depending on the yield of biochar, up to 40% of the total carbon in the biomass can be converted to biochar. Latest findings show, that up to 70% of the biochar may consist of inertinite, which is deemed to have a half-life of more than 1 million years (Sanei, et al., 2024). This is also possible, when biochar is utilised for soil amendment - when applied to agricultural soils, biochar enhances water retention, nutrient retention, and microbial activity, leading to increased crop yields. Recently this also has been acknowledged by the European Commission within the Carbon Removal Certification framework, as biochar is now seen as long-lasting product, with at minimum acknowledged lifetime of more than 35 years.

Co-producing biochar alongside heat or electricity in small-scale biomass combustion systems creates a closed-loop system that maximizes resource efficiency. Instead of viewing biomass combustion solely as an energy production process, biochar production adds value to the biomass feedstock by converting it into a useful soil amendment. This promotes the principles of the circular economy by reducing waste and creating secondary products from biomass resources. Additionally, it opens the application for a broad range of biogenic feedstocks and fuels, as the production of biochar avoids issues of slag formation of ashes.

Overall, the co-production of biochar in small-scale biomass combustion systems has the potential to significantly contribute to carbon sequestration efforts, promote the circular economy, generate renewable energy, and create economic opportunities, making it a promising approach for sustainable resource management and climate change mitigation.

Conclusions

Small-scale biomass combustion has come a long way and continuously developed towards low emission release, high energy efficiency, user friendliness, system integration. A major driver for the developments was on the one hand strict emission thresholds and energy efficiency requirements. Until now they reached a high state-of-the-art and have become a significant and crucial part in today's renewable energy provision.

Of course, these factors play still a significant role in current and future innovations, but also other factors gain more interest like user centricity, sector coupling, circular economy and carbon sequestration.

Constant improvements in energy efficiency and emission reduction are being made. Combustion technologies like fixed bed gasification or zero-flame combustion are perfect examples of this continuous innovation process in small-scale biomass combustion. Besides that, digitalization (home automation and utilisation of forecasting) brings direct effects in real-life operation, whereas hybridisation and combinations of energy technologies allow to flexibly utilize the most climate friendly, environment-protecting and cost-saving option.

Future boilers become more user centric. Home automation and integration of forecasting tools to predict loads and operation of combustion technologies have not only a direct impact on comfort, but also on energy efficiency and emission release. Besides that, combustion performance is also tested during the developments by applying realistic standardized load profiles, giving valuable information on real life emission and energy efficiency – similar to automotive WLTP standards.

Co-production opportunities make small-scale biomass combustion more diverse. Micro combined heat and power (µCHP) technologies have been developed and are already available on the market. Response of the market on these technologies, however, has been hesitant so far due to additional investment costs and increasing interests in photo voltaic technology. Besides CHP, also other co-valorisation opportunities have become interesting. Production of biochar allows for contribution to a circular economy (valorising bio-residues and producing soil amendment) and to carbon sequestration.

To conclude, the journey of small-scale biomass combustion has not ended. It continuously develops further and persistently delivers impact for a renewable, biobased and sustainable future.

Appendices

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